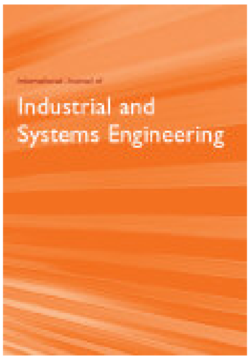


International Journal of Industrial and Systems Engineering

ISSN online: 1748-5045 - ISSN print: 1748-5037
https://www.inderscience.com/ijise

Toward smart manufacturing systems incorporating reconfiguration issues

Ibrahim H. Garbie, Abdelrahman I. Garbie

DOI: 10.1504/IJISE.2021.10041796

Article History:

Received:	23 November 2020
Accepted:	11 May 2021
Published online:	08 January 2024

Toward smart manufacturing systems incorporating reconfiguration issues

Ibrahim H. Garbie*

Department of Mechanical Engineering-Industrial
Engineering Program,
College of Engineering at Helwan,
Helwan University, Cairo, Egypt
Email: garbie68@h-eng.helwan.edu.eg
*Corresponding author

Abdelrahman I. Garbie

Department of Mechanical Engineering,
University of Louisiana at Lafayette,
Lafayette, LA, USA
Email: abdelrahman.garbie1@louisiana.edu

Abstract: Nowadays, Industry 4.0 will become urgently implemented in most developed countries, although it is still mainly conceptual. As there are three different aspects making up Industry 4.0 (I4.0), such as digital systems, biological systems, and physical systems, most of the research published works were focused on mainly the first one. The smart manufacturing system (SMS) is not an invention, although it is representing the heart of I4.0. The SMS is a rebirth of a new version and innovation of production systems taken into consideration reconfiguring the existing manufacturing systems through adding machines with sensors, actuators, and control architectures for achieving the ultimate goals of I4.0. There are many challenges when reconfiguring these systems as an essential requirement to implement I4.0, representing the degree of individual system complexity, reconfigurable machines, material handling systems, system layout, competitive manufacturing strategies, leanness agility, and embedded systems (cyber-physical systems). In this paper, a new perspective of reconfiguring manufacturing systems will be figured out, and the reconfigurability level toward I4.0 will be presented.

Keywords: Industry 4.0; smart manufacturing systems; SMSs; reconfiguration.

Reference to this paper should be made as follows: Garbie, I.H. and Garbie, A.I. (2024) 'Toward smart manufacturing systems incorporating reconfiguration issues', *Int. J. Industrial and Systems Engineering*, Vol. 46, No. 1, pp.1–33.

Biographical notes: Ibrahim H. Garbie is currently a Professor of Industrial Engineering in the Department of Mechanical Engineering at Helwan University in Egypt. He received his PhD in Industrial Engineering from University of Houston, Texas, USA in 2003. He also received his MSc in Manufacturing Engineering and BSc in Production Engineering from Helwan University in Egypt in 1996 and 1991, respectively. His research interests encompass Industry 4.0 and smart manufacturing systems, reconfiguration and sustainability, manufacturing systems analysis and design, lean production,

agile systems, and engineering education. He has authored more than 82 articles in well-regarded international peer reviewed archival journals, conferences, technical reports, and book chapters.

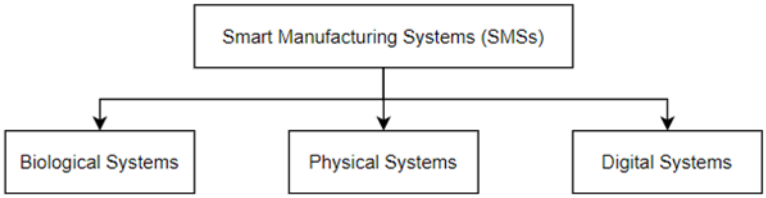
Abdelrahman I. Garbie is currently a postgraduate student in the Department of Mechanical Engineering at University of Louisiana, Lafayette, Louisiana, USA. He received his BSc in Mechanical Engineering from Louisiana State University (LSU) in 2020. His research interests encompass sustainability in mechanical systems, artificial intelligence (AI) and machine learning and Industry 4.0. He is a member of the American Society of Mechanical Engineers (ASME) and others professional societies.

1 Introduction

Smart manufacturing systems (SMSs) are a rebirth of the new version and innovation of existing manufacturing systems into so-called hybrid production systems considering reconfiguring these systems through adding machines with sensors, actuators, and control architectures for achieving Industry 4.0 (I4.0). I4.0 is regarded as the next industrial revolution and is known as I4.0 that will reshape the manufacturing industries besides the previous industrial revolutions (Industry 1.0, Industry 2.0, Industry 3.0) (Garbie 2016, Reischauer 2018), the SMSs is representing the heart of I4.0. SMSs is defined as a reconfigurable hybrid manufacturing systems which are consisting of dedicated systems; focused systems; a job shop remainder cell, and an assembly system taken into consideration the new advanced manufacturing technologies for I4.0. The dedicated systems are representing into automated manufacturing systems while focused systems are concentrating into cellular systems and the associated/corresponding flexible manufacturing cells/systems. A job shop 'remainder' cell is representing into functional and/or process system, and the assembly system is represented by manual and automated assembly system. There are three different aspects/components to build SMSs: physical, digital, and biological systems (see Figure 1). These components are also considered the pillars of I4.0, and they have been structured into technology systems and processes (Dombrowski et al., 2017).

Concerning digital systems, there are different types of devices such as a personal computer (desktop, laptop, smartphones, and video game console) (Moty et al., 2017); industrial internet of thing (IIoT); cyber-physical systems (CPS); information and communication technology (ICT), enterprise architecture (EA) and enterprise integration (Lu, 2017) allows increase/enhance the interaction with the digital world. As the I4.0 is often described as evolution more than revolution, it must keep continuing the digitisation and real-time oriented integration of all elements in the system (Neugebauer et al., 2016). Horizontal integration, end-to-end integration, and vertical integration of the factory are the most recommended activities when implementing I4.0 (Wang et al., 2016 and Garbie and Garbie 2020a, 2020b). Many risks are facing I4.0 representing cyber-attack, malware, spyware, loss of data integrity, or problems with the availability of information, hackers, and software pirates (Tupa et al., 2017). Big data was also recommended as a big challenge facing implementing I4.0.

Figure 1 Elements of SMSs



Concerning physical systems, complexity, agility, and philosophy of lean manufacturing are highly considered through lean automation (Kolberg and Zuhlke, 2015) to optimise the working of smart operators, products, machines, and planners for enabling I4.0 technologies. Plant layout and material handling costs are recommended to be adopted for improving the performance measurements of manufacturing systems (Ingole and Singh, 2021). Reconfiguration was recommended as a significant tool for sustainability in hospital outpatient pharmacies based on the philosophy of group technology (Bashir et al., 2020). Cellular manufacturing systems is recommended as one of most important manufacturing systems type to minimising manufacturing cost and flexibility (Mohtashami et al., 2020).

Interaction between lean manufacturing and I4.0 was mentioned and summarised through process activities and techniques to minimise manufacturing lead time and reducing waste (Bauer et al., 2018). Therefore, lean manufacturing is strongly recommended as a competitive manufacturing strategy and an enabler toward implementing I4.0 (Dombrowski et al., 2017). The agile factory is used as a new facet of I4.0 (Scheuermann et al., 2015), and lean production system is considered as an integrated technical issue and actual impact to implement I4.0 (Wagner et al., 2017). Lean and agile manufacturing are considered the factors of sustainable strategic advantage (Tiwari and Tiwari 2020). Additive manufacturing (AM) systems create flexibilities in innovation of products 'product design and development', mass customisation, and reverse engineering (Haleem et al., 2020). Achieving lean in complex production streams was suggested and presented to solve the whole manufacturing process of product (Samant, and Prakash, 2021).

There are also nine fundamental pillars or enabling technologies for implementing I4.0, such as advanced manufacturing solutions, AM, augmented and virtual reality, simulation; horizontal/vertical integration; IIOT; cloud computing; cyber-security; and big data and analytics. Advanced manufacturing solutions play a crucial role in autonomous and operating toward physical systems of SMS. The implementation of SMSs should take into account the status quo and manufacturing requirements. Most of all, developed countries around the world (especially, the USA, Germany, Japan, and China) tried thoroughly to deploy and promote the strategy implementation of the manufacturing power and speed up the transformation from the manufacturing country to the manufacturing capability.

This paper's primary objective is to figure out how to design manufacturing systems during the era of I4.0, taking into consideration the reconfiguration issues. In addition, the main target of this paper is to formulate and model the re-configurability index for the manufacturing system incorporating these reconfiguration issues toward I4.0. The remainder of this paper is organised as follows: Section 2 presents the literature review. Section 3 describes the research methodology, including the requirements of I4.0, requirements of reconfiguration, challenges of reconfiguration, a reconfiguration methodology, and performance measurements. In Section 4, results and discussion will be presented. Section 5 includes a conclusion which details potential contributions and recommendations for further work.

2 Related review and scope

2.1 Literature review

Nowadays, a very limited few research works have been published in the area of reconfiguration of manufacturing systems as a general concept, and towards I4.0 as a specific. The literature review focuses on answering the following proposed six key research questions (*KRQs*) through the published papers in the journals until now.

- KRQ1: What are the requirements of I4.0?
- KRQ2: What are the requirements of reconfiguration?
- KRQ3: Is designing hybrid-manufacturing systems existing?
- KRQ4: What are the challenges of reconfiguration towards I4.0?
- KRQ5: What is the reconfiguration methodology towards I4.0?
- KRQ6: What are the reconfiguration performance measurements towards I4.0?

In this paper, the six questions will be discussed and investigated in detail in Section 3.

Several published works have been presented in the area of I4.0, but very few of the work mentioned the physical systems 'SMS.' By the way, it is possible to go around the area of SMS and find the relevant research works related to it. They belong to either dedicated systems or focused systems or remainder job shop systems and assembly lines with identifying the challenges facing these systems, reconfiguring them towards I4.0.

Moty et al. (2017) mentioned the framework of implementing I4.0 through investigating the enablers of Italian engineering students to be ready for I4.0. They designed a questionnaire survey to conduct this investigation and analysis. They noticed that students' digital behaviour achieved the highest in their questionnaire more than other representing into digital devices such as desktop/laptop and smartphones followed by videogame console. Lu (2017) conducted an extensive review of published papers in the areas of I4.0 in terms of methodology, CPS, interoperability of I4.0, key technologies, and applications. People are considered the most active factor in productive forces in the area of smart manufacturing (Zhang et al., 2019).

Tupa et al. (2017) suggested different types of risks when implementing I4.0 and how they can be managed in the manufacturing area as an operational risk. They identified seven operational risks as manufacturing process management, maintenance; methods and tools; materials; human resources, machines, and manufacturing technologies, and machine environments. Dombrowski et al. (2017) presented the structure of I4.0 elements into three main categories: technologies, systems, and processes. Technologies representing into big data; RFID; cloud computing; real-time data; augmented and virtual reality; automated guided vehicles, sensor/actuators, and consumer electronics are considered. Systems of I4.0 comprises of smart data/algorithms, intelligent objects;

internet of things; CPS, and machine-t-machine communication. Concerning the process of I4.0, Dombrowski et al. (2017) identified horizontal integration, vertical integration, consisting of information, monitoring, real-time data, visualisation, transparency, flexibility, digitalisation, traceability, and self-optimisation. Santos et al. (2017) presented how to implement a big data system and architecture for I4.0 through specific layers and components.

Kolberg and Zuhlke (2015) used lean automation concepts in implementation I4.0 through lean production in terms of the smart operator, product, machine, and planner. Wang et al. (2016) focused on vertical integration to implement flexible and reconfigurable smart factories taken into consideration industrial wireless networks, cloud computing and fixed or mobile terminals with intelligent elements such as machines, products, and conveyors. Zhang et al. (2019) presented a series of plans and guidelines for smart manufacturing talent education (SMTE) through a reference system including discipline system, training system, practice system, and assessment system. Wagner et al. (2017) identified the impact of I 4.0 on lean production systems through data acquisition and processing, machine-to-machine (M2M) communication, and human-machine interaction (MHI). Haleem et al. (2020) suggested flexibility as a concept in manufacturing system which can be enhanced and improved through the AM in terms of product design, customisation and part printing. Tiwari and Tiwari (2019) identified the lean practices for the automotive small and medium-sized enterprises (SMEs. Tiwari and Tiwari (2020) proposed a novel approach to model green lean and agile manufacturing. Samant and Prakash (2021) proposed an innovative framework to achieve lean performance in terms of productivity, quality, reduced lead-time and cost reduction through using a mix of value stream mapping (VSM) CPLEX optimisation, Arena simulation and lean box score method.

There are few papers focused on the reconfiguration of manufacturing systems for I4.0 as a general. Bortolini et al. (2018) identified five emerging research streams to the upcoming I4.0 through reconfigurability level assessment; analysis of reconfigurable manufacturing systems (RMS) feature; analysis of RMS performances; applied research and field application and reconfigurability toward I4.0. Prasad and Jayswal (2018) proposed measuring the reconfigurability in the manufacturing systems based on cost, effort, and time taken into consideration the scheduling of products. Layout reconfiguration in each planning period was presented based on the minimisation of material handling inside plants and between plants and maximisation of adjacency between departments (Azevedo et al., 2017). Varela et al. (2020) used social network analysis to solve manufacturing systems problems especially in industrial plant layout problem in terms of completion time of jobs (make span), resource utilisation, and throughput time. Ingole and Singh (2021) used plant layout and materials handling costs as an important indicator to improve the revenue of industrial organisation.

A design methodology for changeable manufacturing systems was proposed. It took into consideration the types of manufacturing systems with suitability and physical and logical enablers (Andersena et al., 2017), while Deif and ElMaraghy (2017) considered product variety and volume as a significant dynamic to implement changeable manufacturing systems. Some published papers are also working toward I4.0 in terms of reconfiguration for assembly systems. Bortolini et al. (2017) proposed a framework to investigate the impact of I4.0 principles on the assembly system design. Besides, Cohen et al. (2017) investigated how to transform the resources (machines, workstations) into assembly paradigms to implement I4.0. ElMaraghy and ElMaraghy (2016) depicted the future directions and challenges for implementing smart assembly systems with the perspective of I4.0.

Garbie (2017) and Kusiak (2018) recommended sustainability as one of the most pillars of implementing Smart Manufacturing. Garbie and Al-Shaqsi (2019) introduced a sustainable model for measuring the performance indexes in petroleum companies taking into consideration economic, social and environmental pillar. Garbie and Garbie (2020a) identified the requirements of manufacturing systems for I4.0 including all aspects/issues. The importance of sustainability towards adopting I4.0 was mentioned and discussed in terms of machine design, manufacturing process, and manufacturing systems (Garbie and Garbie, 2020b, 2020c). Mohtashami et al. (2020), presented cellular manufacturing systems as a solution for modern production systems in terms of minimising cost of manufacturing and flexibility in allocating machines. Bashir et al. (2020) proposed a reconfiguration methodology for hospital outpatient pharmacies based on cell formation of drugs for minimising the total distance that pharmacy drug pickers travel to fill prescriptions.

2.2 Research objectives and gaps

The following comments are related to the gap of the review of the literature and suggest the research objectives and goals as follows:

2.2.1 Research gaps

- There is a limited number of publications and fine discussion about the requirements of I4.0 in terms of advanced manufacturing technologies
- Requirements of reconfiguration is still restricted with the machine capacity, machine capability and/or flexibility and the system layout
- There is no any clue about the feasible designing manufacturing systems for I4.0. Most of published works were talking generally without any assigned manufacturing system(s) and which type is recommended
- Challenges of reconfiguration toward I4.0 is not clear in the published papers
- There is no reconfiguration methodology in manufacturing systems for implementing I4.0. The only one is based on the traditional manufacturing systems
- The criteria for performance evaluation due to reconfiguration process is still focusing on traditional performance indexes not ones related to I4.0.

2.2.2 Research objectives

There are six main research objectives (ROs) that must be covered under this topic as follows:

- RO1: Identifying the requirements of I4.0.
- RO2: Identifying the requirements of reconfiguration.
- RO3: Proposing designing hybrid-manufacturing systems.

- RO4: Identifying the challenges of reconfiguration towards I4.0.
- RO5: Updating reconfiguration methodology for I4.0.
- RO6: Updating the reconfiguration performance measurements towards I4.0.

In this paper, the *RO1*, *RO2*, *RO3*, *RO4*, *RO5* and *RO6* will be identified and illustrated among the following section (Section 3) through proposing and identifying the elements of reconfiguration and re-configurability indexes. In addition, these indexes are verified in Section 4 through an illustrative numerical example.

3 Research methodology

In this paper, the blueprint of research methodology is divided into six main streams: requirements of I4.0 'smart manufacturing,' requirements of reconfiguration, designing hybrid-manufacturing systems, challenges of reconfiguration towards I4.0, reconfiguration methodology and processes, and reconfiguration performance measurements and evaluation (Figure 2). Each stream will be discussed and analysed separately. The blueprint is illustrated and expressed as the flow chart of conducting the analysis and investigation toward SMS s in terms of physical systems into three main phases (see Figure 3).

Figure 2 Blueprint of requirements of manufacturing systems toward I4.0

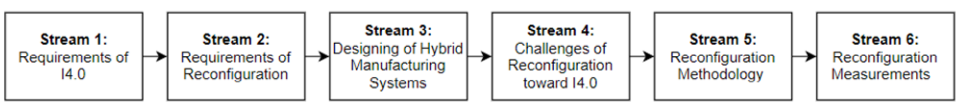
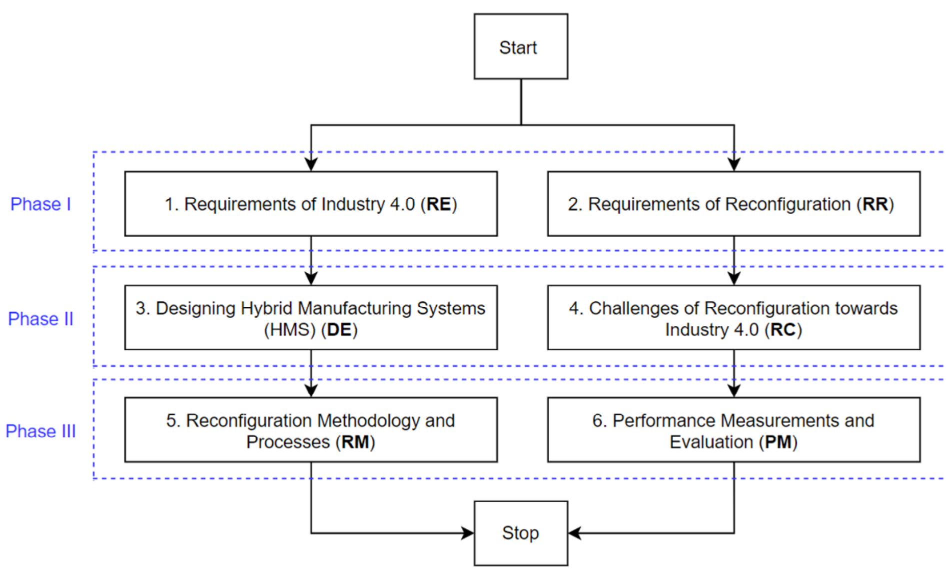


Figure 3 A research methodology (see online version for colours)



3.1 Requirements of I4.0 (RE)

The requirements of I4.0 are divided into design principles and pillars of enabling technologies. SMSs have six identified design principles that are used in their automation and digitisation of their manufacturing processes (see Figure 4). These principles will be discussed as the following:

- Interoperability (A1): indicates flexible collaboration between all components in the manufacturing environment (e.g., assembly stations are not separated from the products produced or workers who are working on them).
- Virtualisation (A2): it is required to monitor the actual processes by using virtual models or models created via simulation.
- Decentralisation (A3): it enables the different systems within the smart plant to make decisions autonomously.
- Real-time capability (A4): requires the manufacturing process of collecting data, feedback, and monitoring processes to work in real-time.
- Service orientation (A5): A smart plant requires internal and external services through the internet of service (IoS).
- Modularity (A6): flexibility and agility [of products, manufacturing systems, and material handling systems (MHSs)] are required urgently for smart manufacturing to adapt to changing circumstances quickly.

The design principles of I4.0 at any time *t*, $RE1(t)$, is represented by the six principles as follows as the following equation.

$$RE1(t) = f(A1, A2, A3, A4, A5, A6) \tag{1}$$

In terms of requirements regarding enabling technologies, there are nine pillars of enabling technologies for implementing SMS s representing into advanced manufacturing solutions (P1); AM (P2); augmented and virtual reality (P3); simulation (P4); horizontal/vertical integration (P5); IIoT (P6); cloud computing (P7); cyber-security and big data analytics (P9) (see Figure 4). Therefore, SMS s becomes so essential to the future of manufacturing.

Figure 4 Mapping between design principles and enabling technologies for SMSS (see online version for colours)

Six design principles of industry 4.0
1.Interoperability (A1)
2. Virtualization (A2)
3. Decentralization (A3)
4. Real time capability (A4)
5. Service orientation (A5)
6. Modularity (A6)

Nine Pillars of enabling technologies for implementing SMSs
1.Advanced manufacturing solutions (P1)
2. Additive manufacturing (P2)
3. Augmented and virtual reality (P3)
4. Simulation (P4)
5. Horizontal/vertical integration (P5)
6. Industrial internet of thing (IIoT) (P6)
7. Cloud computing (P7)
8. Cyber-security (P8)
9. Big data analytics (P9)

The design requirements of I4.0 at any time t, $RE2(t)$, is represented by the nine enabling technologies as the following equation.

$$RE2(t) = f(P1, P2, P3, \ldots, P9) \tag{2}$$

In this paper, modularity as a design principle integrated with advanced manufacturing solutions is closer to designing SMS s, taking flexibility and agility into consideration. Therefore, the requirements of I4.0 at any time t, $RE(t)$, can be represented by the interaction of equation (3) and equation (4) as the following equations.

$$RE(t) = f\{RE1(t)\} \cap f\{RE2(t)\} \tag{3}$$

$$RE(t) = f(A6, P1) \tag{4}$$

Equation (4) is used to represent the requirements of I4.0 only without estimation. The evaluation and measuring the demands of I4.0 will be presented after modification for two aspects, as shown in equation (5) and later in equation (7). The index of equation (5) is based on the average of the normalisations values of all elements of equation (4) which are representing into modularity and advanced manufacturing solutions.

$$RE(t) = \frac{\sum_{i=1}^{n_i j} x_i j(t)}{n_{ij}(t)} \tag{5}$$

where

$n_{ij}(t)$ number of elements at any time t in equation (4) and/or equation (5)

$$X^{ij}(t) = \frac{E^{ij} - X_{min}^{ij}}{X_{max}^{ij} - X_{min}^{ij}} \tag{6}$$

$X^{ij}(t)$ represents the aspects in each enabler i with each requirement j at any time t

$n_{ij}(t)$ represents the number of enablers in each requirement at any time t

E^{ij} represents the existing value of enabler i with respect to requirement j at any time t

X_{max}^{ij} represents the maximum value of enabler i with respect to requirement j at any time t

X_{min}^{ij} represents the minimum value of enabler i with respect to requirement j at any time t.

Then, equation (5) can be rewritten as the following equation (7)

$$RE(t) = \frac{\left(X^{A6}(t) + X^{P2}(t)\right)}{2} \tag{7}$$

where

$$X^{A6}(t) = \frac{E^{A6} - X_{min}^{A6}}{X_{max}^{A6} - X_{min}^{A6}} \tag{8}$$

E^{A6} represents the existing level of modularity at any time t

X_{max}^{A6} represents the maximum level of modularity at any time t

X_{min}^{A6} represents the minimum level of modularity at any time t

and

$$X^{P1}(t) = \frac{E^{P1} - X_{min}^{P1}}{X_{max}^{P1} - X_{min}^{P1}} \tag{9}$$

E^{P1} represents the existing level of using advanced manufacturing solutions at any time t

X_{max}^{P1} represents the maximum level of using advanced manufacturing solutions at any time t

X_{min}^{P1} represents the minimum level of using advanced manufacturing solutions at any time t.

3.2 Requirements of reconfiguration (RR)

Traditionally and classically, a RMS is designed for rapid adjustment to customised production capacity and capability, in response to new circumstances (such as introducing a new product (*B*1); modifying the existing one(s) (*B*2) and changes in forecasting demand (*B*3). It is done by rearranging and changing components of the hybrid manufacturing system itself (Garbie 2014 a, b). For this reason, the RMS is a new manufacturing philosophy that will allow flexibility not only in producing a variety of products (parts) and changing market demands but will also change the system itself. There are many different types of activities for reconfiguring hybrid manufacturing systems such as routing, scheduling, planning, programming of machines (e.g., CNC), controlling, physical layout by adding and removing machines and their components, MHSs, and configuration of machines into workstations (cells) (Garbie, 2014a, 2014b).

The essential aspects of the hybrid manufacturing system are the design of the system integrating facilities, design, and logistics. Therefore, designing a manufacturing system is divided into three main streams: production system, MHS, and plant layout system (Garbie, 2014a, 2014b). In reconfiguration processes, the new configuration of the manufacturing system will be created and reconfigured based on the original system plus or minus new components. These components are machines, equipment, tools, and a new layout. The production systems are classified as a flow shop (e.g., assembly line either manual or automated), functional or process (job shop), or cellular system and the associated flexible manufacturing cell/system. Also, the MHS in any production system plays a vital role in the performance of the entire manufacturing system, although it was considered as non-productive equipment (means non-value added). Regarding the production system layout, it has a very significant correlation with the structure and operation of a production system.

Therefore, the requirements of reconfiguration regarding I4.0 will need not only the previous traditional issues which were mentioned but also adding new intelligent CPS such as sensor (*B*4) and actuators (*B*5). Therefore, the automation and information system will be urgent and necessary in the reconfiguration processes, and their integration and real-time monitoring will also be a new performance measurement.

The requirements of reconfiguration (*RR*) can be represented by the following equation as follows:

$$RR(t) = f(B1, B2, B3, B4, B5) \tag{10}$$

Equation (10) can be rewritten as the following equation (11) for assessing the $RR(t)$ index at any time t regarding the requirements of reconfiguration. The index of equation (11) is based on the average of the normalisations values of all elements of equation (10).

$$RR(t) = \frac{\sum_{i=1}^{n_{ij}} B_i(t)}{n_{ij}(t)} \tag{11}$$

where

$n_{ij}(t)$ number of elements at any time t in equation (10) and/or equation (11)

$$X^{B1}(t) = \frac{E^{B1} - X_{min}^{B1}}{X_{max}^{B1} - X_{min}^{B1}} \tag{12}$$

E^{B1} represents the existing level of new products at any time t

$X_{\max}^{B1}$ represents the maximum level of new products at any time t

X_{min}^{B1} represents the minimum level of new products at any time t

$$X^{B2}(t) = \frac{E^{B2} - X_{min}^{B2}}{X_{max}^{B2} - X_{min}^{B2}} \tag{13}$$

E^{B2} represents the existing percentage to modifying current products at any time t

$X_{\max}^{B2}$ represents the maximum percentage to modifying current products at any time t

$X_{\min}^{B2}$ represents the minimum percentage to modifying current products at any time t

$$X^{B3}(t) = \frac{E^{B3} - X_{min}^{B3}}{X_{max}^{B3} - X_{min}^{B3}} \tag{14}$$

E^{B3} represents the existing percentage of changing demand at any time t

$X_{\max}^{B3}$ represents the maximum percentage of changing demand at any time t

$X_{\min}^{B3}$ represents the minimum percentage of changing demand at any time t

$$X^{B4}(t) = \frac{E^{B4} - X_{min}^{B4}}{X_{max}^{B4} - X_{min}^{B4}} \tag{15}$$

E^{B4} represents the existing percentage of using sensors in the whole plant at any time t

$X_{\max}^{B4}$ represents the maximum percentage of using sensors in the whole plant at any time t

$X_{\min}^{B4}$ represents the minimum percentage of using sensors in the whole plant at any time t

$$X^{B5}(t) = \frac{E^{B5} - X_{min}^{B5}}{X_{max}^{B5} - X_{min}^{B5}} \tag{16}$$

E^{B5} represents the existing percentage of using actuators in the whole plant at any time t

$X_{\max}^{B5}$ represents the maximum percentage of using actuators in the whole plant at any time t

$X_{\min}^{B5}$ represents the minimum percentage of using actuators in the whole plant at any time t.

Integrating between the requirements of I4.0 (RE) and the requirements of reconfiguration (RR) is represented by Figure 5 to summarise the phase I toward SMS s. It seems from Figure 5 that there is a strong integrating between RE and RR through A6, P1, and B1 until B5. This means that A6, which is represented in modularity-flexibility and agility, has a relationship with B1, B2, B3, B4, and B5. In addition, P1, which is focusing on advanced manufacturing solutions, in terms of physical systems, especially hybrid manufacturing systems, has the same relationships and concentrations on RR.

Figure 5 Integration between RE and RR (see online version for colours)

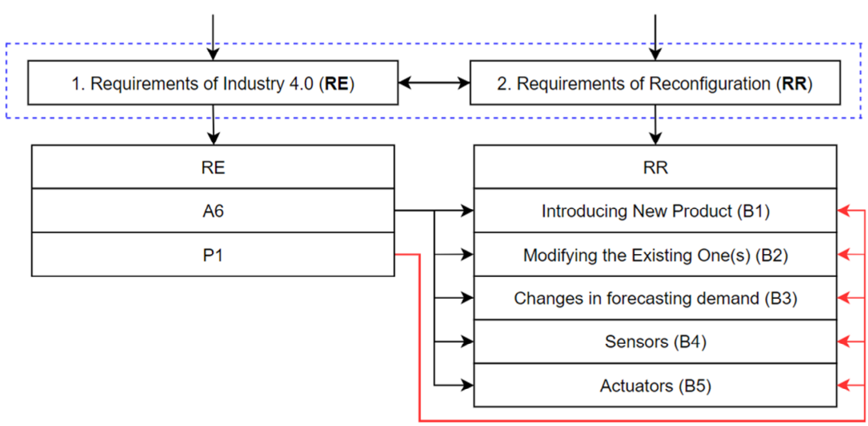
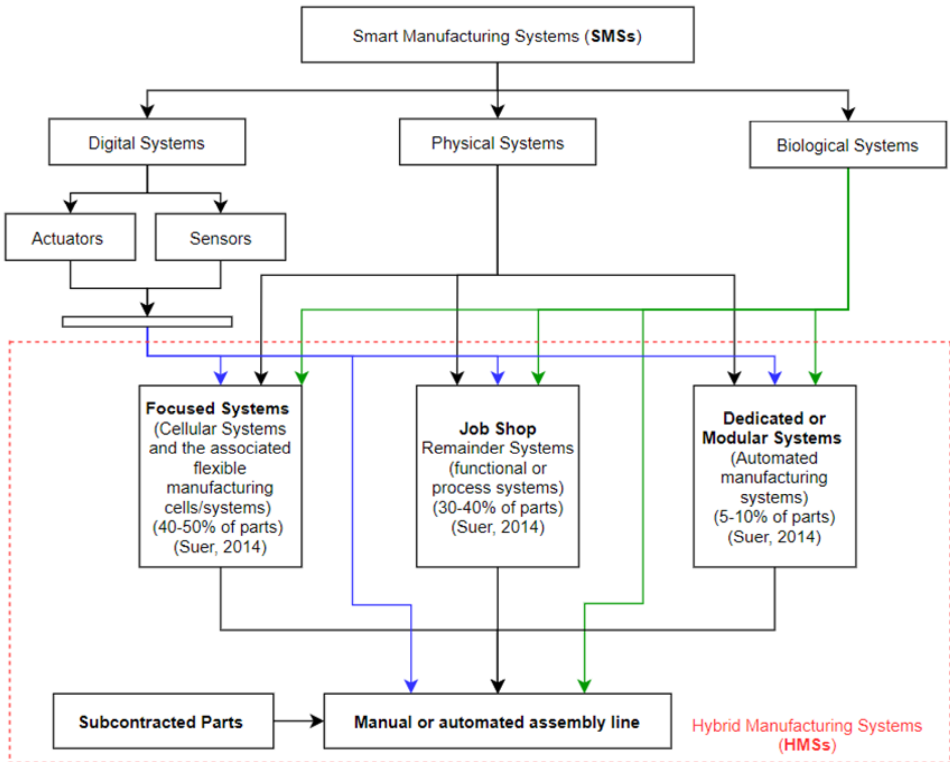


Table 1 Analysis of elements of physical system of SMSs

	Layout (C1)	*Machines (C2)*	*Material handling systems (C3)*	*Expansion (C4)*	*Routing (C5)*	*Automation (C6)*
Dedicated/ Modular system DS	Line product layout	Dedicated machines with rigid structure	Conveying systems	Just logical expansion or duplicating system	Fixed routing between machine or stations	Automated
Job shop (Remainder) JS	Functional/ process layout	CNC machines	Automated guided vehicles (AGVs)	Limited	Variable	Automated
Flexible manufacturing systems FMS	Single machine, flexible cell or system	CNC machines	Automated material handling (Conveyors, AGVs, Robots, Cranes)	Just logical expansion or duplicating system	Alternate routing between machine or stations	Automated
Assembly system AS	Line product layout	Dedicated machines and tools	Automated material handling equipment (Conveyors)	Only duplicating system	Fixed routing between stations	Automated/manual systems

Figure 6 Types of different manufacturing systems for HMSS (see online version for colours)



3.3 Designing hybrid manufacturing systems (HMSs) (DE)

The hybrid manufacturing system SMS is not an invention. It is a rebirth of a new version of reconfiguring manufacturing systems 'consisting of dedicated systems- product layout; remainder cells-process and functional layout; cellular cells/system and the associated/upgrading flexible manufacturing cells/system, and finally assembly systems' added by equipped machines with sensors, actuators and control architectures for achieving I4.0 (Figure 6). As a SMS (plant) is considered as the heart of I4.0, the HMS hosts intelligent manufacturing processes. This means that there are many smarts in the plant/factory to be so-called smart such as smart product, smart building/layout, smart logistics/material handling equipment; smart produce; smart mobility; smart tools, and finally smart machine. Designing hybrid manufacturing systems is consisting of dedicated or modular manufacturing systems (automated) (DS), flexible manufacturing systems (FMS), automated Job shop system (remainder cells) (JS), and automated/manual assembly system (AS). The characteristics of each type of manufacturing are illustrated in Table 1, according to Figure 6. It seems from Figure 6 that sensors and actuators belong to a digital system that will be distributed among all machines/equipment and assembly workers/stations to get the data from them. The biological systems will be used to collect the waste/residual from different types of the hybrid manufacturing system.

Concerning assembly system, using IIoT to assembly line/process is considered the keystone of smart assembly because every assembly station or storage location or equipment, and product or worker in the assembly line will be sensitised to communicate in real-time specific data (Bortolini et al., 2017; Cohen et al., 2017). These can be done by supporting the assembly line with aided assembly for workers (operator support system), intelligent storage management, self-configured workstation layout, product and process traceability, and late customisation and control system.

Designing physical system of SMS 'HMS', initially and physically, is based on the following issues: types of layout ($C1$), reconfigurable machines ($C2$), MHS ($C3$), plant or system expansion ($C4$), routing ($C5$), and type of automation ($C6$). The following equation is used to represent the previous issues in designing, initially, the manufacturing system as:

$$DE(t) = f(C1, C2, C3, C4, C5, C6) \tag{17}$$

Equation (17) is rewritten as the following equation (18) for assessing the $DE(t)$ index at any time t regarding designing physical system of SMS. The index of equation (18) is based on the average of the normalisations values of all elements of equation (17).

$$DE(t) = \frac{\sum_{i=1}^{n_{ij}} C_i(t)}{n_{ij}(t)} \tag{18}$$

where

$n_{ij}(t)$ number of elements at any time t in equation (17) and/or equation (18)

$$X^{C1}(t) = \frac{E^{C1} - X_{min}^{C1}}{X_{max}^{C1} - X_{min}^{C1}} \tag{19}$$

E^{C1} represents the existing efficiency of layout at any time t

$X_{\max}^{C1}$ represents the maximum existing efficiency of plant layout at any time t

$X_{\min}^{C1}$ represents the minimum existing efficiency of plant layout at any time t.

Efficiency of plant layout is measured based on the maximum and/or minimum closeness between departments

$$X^{C2}(t) = \frac{E^{C2} - X_{min}^{C2}}{X_{max}^{C2} - X_{min}^{C2}} \tag{20}$$

E^{C2} represents the existing number of reconfigurable machines at any time t

$X_{\max}^{C2}$ represents the maximum number of reconfigurable machines at any time t

$X_{\min}^{C2}$ represents the minimum number of reconfigurable machines at any time t.

$$X^{C3}(t) = \frac{E^{C3} - X_{min}^{C3}}{X_{max}^{C3} - X_{min}^{C3}} \tag{21}$$

E^{C3} represents the existing percentage of flexibility in MHSs at any time t

$X_{\max}^{C3}$ represents the maximum percentage of flexibility in MHSs at any time t

$X_{\min}^{C3}$ represents the minimum percentage of flexibility in MHSs at any time t.

Measuring flexibility of material handling is based on the number of different types of material handling equipment used in the plant/factory

$$X^{C4}(t) = \frac{E^{C4} - X_{min}^{C4}}{X_{max}^{C4} - X_{min}^{C4}} \tag{22}$$

E^{C4} represents the existing percentage of expansion in the plant at any time t

$X_{\max}^{C4}$ represents the maximum percentage of expansion in the plant at any time t

$X_{\min}^{C4}$ represents the minimum percentage of expansion in the plant at any time t

$$X^{C5}(t) = \frac{E^{C5} - X_{min}^{C5}}{X_{max}^{C5} - X_{min}^{C5}} \tag{23}$$

E^{C5} represents the existing percentage of routing flexibility in the plant at any time t

$X_{\max}^{C5}$ represents the maximum percentage of routing flexibility in the plant at any time t

$X_{\min}^{C5}$ represents the minimum percentage of routing flexibility in the plant at any time t.

Routing flexibility is measured as using different routes in the plants/factories if there is shutdown or breakdown of machines/equipment

$$X^{C6}(t) = \frac{E^{C6} - X_{min}^{C6}}{X_{max}^{C6} - X_{min}^{C6}} \tag{24}$$

E^{C6} represents the existing level of automation in the plant at any time t

$X_{\max}^{C6}$ represents the maximum level of automation in the plant at any time t

$X_{\min}^{C6}$ represents the minimum level of automation in the plant at any time t.

3.4 Challenges of reconfiguration (RC)

There are many challenges facing manufacturing systems to be reconfigured respectively into main challenges such as complexity, reconfigurable machines; competitive manufacturing strategies (lean and agile manufacturing); automation level, and embedded systems representing into CPSs. Although these identified challenges are well-known for all academicians and practitioners in the area of industrial, manufacturing and systems engineering, they are still unexploited and/or discussed individually. It is recommended to analyse and incorporate all of them in one formula. For each type of manufacturing system, the level of challenge will be different in terms of elements. For example, dedicated systems, the complexity level is medium focusing on the structure of the system. However, in job shop systems or FMS or assembly one, the complexity level is high not only in the system structure itself (design) but also in the system dynamics (operating). Concerning the complexity of machines, most machines are automated. Updating/upgrading machines is not a simple task. It needs more high technologies/aspects. Therefore, the level of complexity is high and requires more attention regarding maintenance (preventive and predictive). The level of complexity will differ from one type to another based on the layout and material handling equipment.

For competitive manufacturing strategies, lean manufacturing has a significant effect on implementing I4.0 (Kolberg and Zuhlke, 2015), but the level of manufacturing leanness will also be different on each type. For dedicated, flexible manufacturing and assembly systems, the level of leanness will be high (minimum waste), but in Job Shop manufacturing systems, it becomes low or at least medium. The agility level is affected by each type of manufacturing system. FMS had the highest level of agility following by the job shop. In dedicated manufacturing systems, the level of agility is the lowest one.

Regarding the current automation level, the level of challenges toward updating it is low according to all types of manufacturing systems. In modern/smart manufacturing and because of digitalisation, the manufacturing systems, especially the manufacturing processes, will be operated by intelligent CPS. As digitalisation technologies play a vital role in transformation, the manufacturing processes that digitise the different manufacturing systems are not easy and represent a significant challenge to implement I4.0 or 'smart manufacturing.'

Figure 7 Integration between DE and RC (see online version for colours)

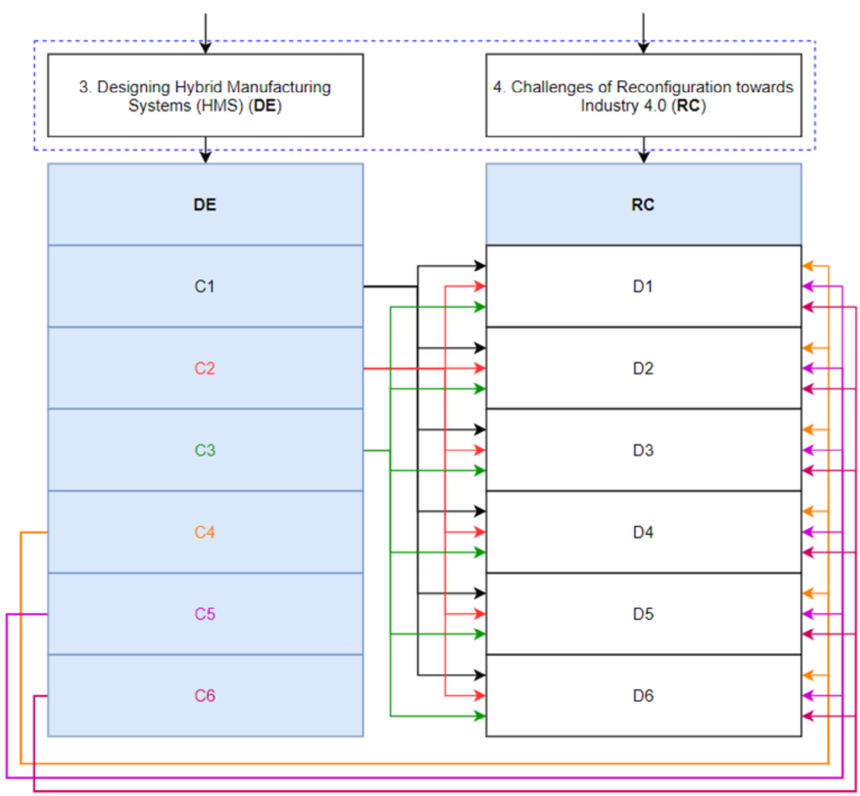


Table 2 analysis of challenges regarding reconfiguration for SMSs

Challenges	*Complexity (D1)*		*Reconfigurable machine(s) (D2)*	*Competitive strategies (D3)*		*Cyber physical systems*		
Manufacturing types	*Static*	*Dynamic*		*Lean*	*Agile*	*Automation (D4)*	*Sensor (D5)*	*Actuators (D6)*
Dedicated system (DS)	Low	Low	High	Low	Low	Low	Low	Low
Job shop (JS)	Medium	High	Medium	High	Low	Low	Low	Low
Flexible manufacturing system (FMS)	Medium	Low	Low	Low	Low	Low	Low	Low
Assembly system (AS)	Low	low	Low	low	Low	Low	Low	Low

Table 2 shows the level of implementing I4.0 with the challenges with different types of manufacturing systems to comprise the hybrid manufacturing system. This level is divided into three categories: low, medium, and high. Low-level means it is easy to implement, and a high level means it is challenging to implement it. It can be observed from Table 2 that the requirements of I4.0 from the CPS is not complicated as a challenge, but the problem represents the designing system, including optimising complexity, reconfigurable machines/systems, and conducting competitive strategies.

Therefore, the challenges of reconfiguration at any time t, $RC(t)$ is formulated as a function of complexity ($D1$), reconfigurable machines ($D2$), competitive strategies ($D3$), automation ($D4$) and cyber physical system (sensors ($D5$) and actuators ($D6$) as follows in equation (25).

$$RC(t) = f(D1, D2, D3, D4, D5, D6) \tag{25}$$

Equation (25) can be rewritten as the following equation (26) for assessing the $RC(t)$ index at any time t regarding challenges of reconfiguration (RC). The index of equation (26) is based on the average of the normalisations values of all elements of equation (25).

$$RC(t) = \frac{\sum_{i=1}^{n_{ij}} D_i(t)}{n_{ij}(t)} \tag{26}$$

where

$n_{ij}(t)$ number of elements in equation (25) and/or equation (26)

$$X^{D1}(t) = \frac{E^{D1} - X_{min}^{D1}}{X_{max}^{D1} - X_{min}^{D1}} \tag{27}$$

E^{D1} represents the existing level of manufacturing complexity at any time t

$X_{\max}^{D1}$ represents the maximum level of manufacturing complexity at any time t

$X_{\min}^{D1}$ represents the minimum level of manufacturing complexity at any time t

Manufacturing complexity is measured based on the degree of complexity inside the plant/factory due to so many issues such as machines, human resources, business operations, etc.

$$X^{D2}(t) = \frac{E^{D2} - X_{min}^{D2}}{X_{max}^{D2} - X_{min}^{D2}} \tag{28}$$

E^{D2} represents the existing number reconfigurable machines in plant/factory at any time t

$X_{\max}^{D2}$ represents the maximum number reconfigurable machines in plant/factory at any time t

$X_{\min}^{D2}$ represents the minimum number reconfigurable machines in plant/factory at any time t

$$X^{D3}(t) = \frac{E^{D3} - X^{D3}_{min}}{X^{D3}_{max} - X^{D3}_{min}} \quad (29)$$

E^{D3} represents the existing level of applying competitive manufacturing at any time *t*

$X^{D3}_{\max}$ represents the maximum level of applying competitive manufacturing at any time *t*

$X^{D3}_{\min}$ represents the minimum level of applying competitive manufacturing at any time *t*.

Competitive manufacturing is measured based on the level of manufacturing leanness and manufacturing agility.

$$X^{D4}(t) = \frac{E^{D4} - X^{D4}_{min}}{X^{D4}_{max} - X^{D4}_{min}} \quad (30)$$

E^{D4} represents the existing level of required automation in the plant/factory at any time *t*

$X^{D4}_{\max}$ represents the maximum level of required automation in the plant/factory at any time *t*

$X^{D4}_{\min}$ represents the minimum level of required automation in the plant/factory at any time *t*.

Automation level is measured based on how much of automation level needed more than manned level

$$X^{D5}(t) = \frac{E^{D5} - X^{D5}_{min}}{X^{D5}_{max} - X^{D5}_{min}} \quad (31)$$

E^{D5} represents the existing level of using sensors in the plant/factory at any time *t*

$X^{D5}_{\max}$ represents the maximum level of using sensors in the plant/factory at any time *t*

$X^{D5}_{\min}$ represents the minimum level of using sensors in the plant/factory at any time *t*.

$$X^{D6}(t) = \frac{E^{D6} - X^{D6}_{min}}{X^{D6}_{max} - X^{D6}_{min}} \quad (32)$$

E^{D6} represents the existing level of using actuators in the plant/factory at any time *t*

$X^{D6}_{\max}$ represents the maximum level of using actuators in the plant/factory at any time *t*

$X^{D6}_{\min}$ represents the minimum level of using actuators in the plant/factory at any time *t*.

Integrating between the designing of hybrid manufacturing systems (DE) and the challenges of reconfiguration (RC) is illustrated in Figure 7 to summarise the phase II toward SMS s. It seems from Figure 7 that there is a strong integrating between DE and RC through their enablers. This means that enablers of DE have a relationship with the enablers of RC.

3.5 A reconfiguration methodology (RM)

As mentioned in Garbie (2014a), additional to sensors and actuators, a reconfiguration methodology will be suggested and presented based on the existing manufacturing systems types and layout (E1) and MHSs (E2) with their material handling equipment's and identification systems (E3).

Therefore, the reconfiguration methodology at any time *t*, *RM* (*t*) is formulated as a function of the previous issues (*E*1, *E*2, and *E*3) as follows in equation (33).

$$RM(t) = f(E1, E2, E3) \tag{33}$$

Equation (33) can be rewritten as the following equation (34) for assessing the *RM*(*t*) index at any time *t* regarding reconfiguration methodology (*RM*). The index of equation (34) is based on the average of the normalisations values of all elements of equation (33).

$$RM(t) = \frac{\sum_{i=1}^{n_{ij}} E_i(t)}{n_{ij}(t)} \tag{34}$$

where

$n_{ij}(t)$ number of elements in equation (33) and/or equation (34)

$$X^{E1}(t) = \frac{E^{E1} - X_{min}^{E1}}{X_{max}^{E1} - X_{min}^{E1}} \tag{35}$$

E^{E1} represents the existing type of manufacturing systems design and layout at any time t

$X_{\max}^{E1}$ represents the maximum type of manufacturing systems design and layout at any time *t*

$X_{\min}^{E1}$ represents the minimum type of manufacturing systems design and layout at any time *t*.

$$X^{E2}(t) = \frac{E^{E2} - X_{min}^{E2}}{X_{max}^{E2} - X_{min}^{E2}} \tag{36}$$

E^{E2} represents the existing type of MHSs design at any time *t*

$X_{\max}^{E2}$ represents the maximum type of MHSs design at any time *t*

$X_{\min}^{E2}$ represents the minimum type of MHSs design at any time *t*.

MHSs design is based on how many different designs of MHS will be available and used.

$$X^{E3}(t) = \frac{E^{E3} - X_{min}^{E3}}{X_{max}^{E3} - X_{min}^{E3}} \tag{37}$$

E^{E3} represents the existing type of identification systems design at any time *t*

$X_{\max}^{E3}$ represents the maximum type of identification systems design at any time t

$X_{\min}^{E3}$ represents the minimum type of identification systems design at any time t.

Identification systems design is measured based on how many different identification systems will be available and used.

3.6 Performance measurement (PM)

Regarding performance measurement, there are eight crucial primary performance objectives such as cost ($F1$), responsiveness ($F2$), system productivity ($F3$), people behaviour ($F4$), work in progress (WIP) ($F5$), and quality ($F6$) (Garbie, 2014b) additional to the real-time monitoring ($F7$) and the efficiency/reliability/availability of collecting the data ($F8$). Therefore, the performance measurement at any time t, $PM(t)$, is formulated as a function of the previous issues ($F1$, $F2$, …, $F8$) as follows in equation (38).

$$PM(t) = f(F1, F2, ..., F8) \tag{38}$$

Equation (38) can be rewritten as the following equation (39) for assessing the $PM(t)$ index at any time t regarding performance measurement (PM). The index of equation (39) is based on the average of the normalisations values of all elements of equation (38).

$$PM(t) = \frac{\sum_{i=1}^{n_{ij}} F_i(t)}{n_{ij}(t)} \tag{39}$$

where

$n_{ij}(t)$ number of elements in equation (38) and/or equation (39)

$$X^{F1}(t) = \frac{E^{F1} - X_{min}^{F1}}{X_{max}^{F1} - X_{min}^{F1}} \tag{40}$$

E^{F1} represents the existing unit cost at any time t

$X_{\max}^{F1}$ represents the maximum unit cost at any time t

$X_{\min}^{F1}$ represents the minimum unit cost at any time t.

Unit cost is used to measure the range of unit cost due to reconfiguration

$$X^{F2}(t) = \frac{E^{F2} - X_{min}^{F2}}{X_{max}^{F2} - X_{min}^{F2}} \tag{41}$$

E^{F2} represents the existing response manufacturing time at any time t

$X_{\max}^{F2}$ represents the maximum response manufacturing time at any time t

$X_{\min}^{F2}$ represents the minimum response manufacturing time at any time t.

Response-manufacturing time is the time to produce a product starting from customer order until receive it.

$$X^{F3}(t) = \frac{E^{F3} - X_{min}^{F3}}{X_{max}^{F3} - X_{min}^{F3}} \tag{42}$$

E^{F3} represents the existing production rate at any time *t*

$X_{\max}^{F3}$ represents the maximum production rate at any time *t*

$X_{\min}^{F3}$ represents the minimum production rate at any time *t*.

$$X^{F4}(t) = \frac{E^{F4} - X_{min}^{F4}}{X_{max}^{F4} - X_{min}^{F4}} \tag{43}$$

E^{F4} represents the existing number of people resisting implementation I4.0 at any time t

$X_{\max}^{F4}$ represents the maximum number of people resisting implementation I4.0 at any time *t*

$X_{\min}^{F4}$ represents the minimum number of people resisting implementation I4.0 at any time *t*.

Number of employees resisting implementing I4.0 is measured based on the range of employees whom will reject implementing I 4.0.

$$X^{F5}(t) = \frac{E^{F5} - X_{min}^{F5}}{X_{max}^{F5} - X_{min}^{F5}} \tag{44}$$

E^{F5} represents the existing number of units in WIP at any time *t*

$X_{\max}^{F5}$ represents the maximum number of units in WIP at any time *t*

$X_{\min}^{F5}$ represents the minimum number of units in WIP at any time *t*.

$$X^{F6}(t) = \frac{E^{F6} - X_{min}^{F6}}{X_{max}^{F6} - X_{min}^{F6}} \tag{45}$$

E^{F6} represents the existing percentage of quality control at any time *t*

$X_{\max}^{F6}$ represents the maximum percentage of quality control at any time *t*

$X_{\min}^{F6}$ represents the minimum percentage of quality control at any time *t*.

$$X^{F7}(t) = \frac{E^{F7} - X_{min}^{F7}}{X_{max}^{F7} - X_{min}^{F7}} \tag{46}$$

E^{F7} represents the existing percentage of using real time monitoring at any time t

$X^{F7}_{\max}$ represents the maximum percentage of using real time monitoring at any time t

$X^{F7}_{\min}$ represents the minimum percentage of using real time monitoring at any time t.

$$X^{F8}(t) = \frac{E^{F8} - X^{F8}_{min}}{X^{F8}_{max} - X^{F8}_{min}} \tag{47}$$

E^{F8} represents the existing reliability of collecting data at any time t

$X^{F8}_{\max}$ represents the maximum reliability of collecting data at any time t

$X^{F8}_{\min}$ represents the minimum reliability of collecting data at any time t.

Degree or percent of accurate the data collection and the range of accuracy is used to measure the reliability of collecting data from machines/equipment.

Figure 8 Integration between DE and RC (see online version for colours)

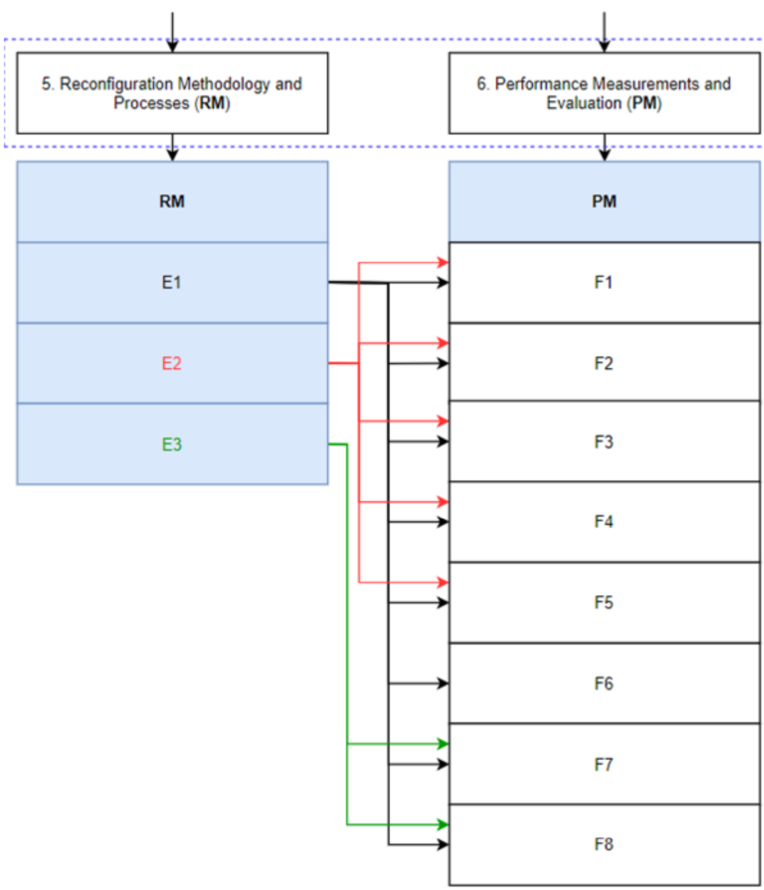


Table 3 Data towards SMS

I4.0	*Requirements*	*Enabler*	*Key performance indicators (KPI)*	*Performance metrics*		
				Existing value	*Target value*	
					Max	*Min*
SMS	RE	A6	Level of modularity	85	100	80
		P2	Level of using advanced manufacturing technologies and solutions	90	100	85
	RR	B1	Number of new products	6	10	5
		B2	Percentage of modification towards current products	3	4	2
		B3	Percentage of changing demand	30	50	20
		B4	Percentage of using sensors in the whole plant	80	100	70
		B5	Percentage of using sensors in the whole plant	80	100	70
	DE	C1	Efficiency of layout design	85	100	75
		C2	Number of reconfigurable machines	50	70	40
		C3	Percentage of flexibility in material handling systems	75	100	70
		C4	Percentage of expansion in the plant/factory	15	40	10
		C5	Percentage of routing flexibility in the plant/factory	70	90	50
		C6	Level of automation in the plant/factory	60	80	50
	RC	D1	Level of manufacturing complexity	50	60	20
		D2	Number of reconfigurable machines in the plant/factory	50	70	40
		D3	Level of applying competitive manufacturing	70	100	60
		D4	Level of required automation in the plant/factory	85	100	70
		D5	Percentage of using sensors in the plant/factory	80	100	70
		D6	Percentage of using actuators in the plant/factory	80	100	70
	RM	E1	Different types of manufacturing systems design and layout	4	4	3
		E2	Different types of material handling systems design	3	3	2
		E3	Different types of identification systems design	4	7	3
	PM	F1	Unit cost (S/unit)	50	55	45
		F2	Manufacturing response time (Days)	12	15	7
		F3	Production rate (Units/hour)	100	120	80
		F4	Number of employees resist implementing I4.0	50	60	40
		F5	Number of units in WIP	300	350	150
		F6	Quality control level	90	100	90
		F7	Percentage of using real time monitoring	95	100	90
		F8	Reliability of collecting data	95	100	90

Table 4 Indexes of streams and re-configurability toward SMS

I4.0	*Requirements*	*Enabler*	*Normalised value*	*Index of the requirement*	*Relative weights*	*RI (t)*
SMS	RE	A6	0.25	0.290	0.287	0.424
		P2	0.33			
	RR	B1	0.20	0.338	0.145	
		B2	0.50			
		B3	0.33			
		B4	0.33			
		B5	0.33			
	DE	C1	0.40	0.400	0.161	
		C2	0.33			
		C3	0.17			
		C4	0.17			
		C5	0.50			
		C6	0.33			
	RC	D1	0.75	0.415	0.178	
		D2	0.33			
		D3	0.25			
		D4	0.50			
		D5	0.33			
		D6	0.33			
	RM	E1	1.00	0.750	0.138	
		E2	1.00			
		E3	0.25			
	PM	F1	0.50	0.550	0.092	
		F2	0.62			
		F3	0.50			
		F4	0.50			
		F5	0.75			
		F6	0.50			
		F7	0.50			
		F8	0.50			

Integrating between the reconfiguration methodology and process (RM) and the performance measurements and evaluation (PM) is illustrated in Figure 8 to summarise the phase III toward SMS s. It seems from Figure 8 that there is a strong relationship between enablers of RM and PM, especially the E1 'type of manufacturing system.'

Therefore, the reconfigurability index (RI) toward I4.0 is formulated as a function of requirements of I4.0 (RE), requirements of reconfiguration (RR), designing systems (DE), challenges of reconfiguration (RC), reconfiguration methodology (RM), and performance measurements and performances (PM) as follows in equation (48)

$$RI = f(RE, RR, DE, RC, RM, PM) \quad (48)$$

Equation (48) can be rewritten as the following equations (49) and (50). Each term in equation (50) represents a value of sub-re-configurability of SMSs. Adding these terms with relative weights is considered. These weights can be used as an existing reason to differentiate between major streams of reconfiguration. The re-configurability model in equation (50) is used to estimate the re-configurability assessment (*RI*) of a SMS.

$$RI = \sum_{i=1}^{n=6} w_{ij} X_{ij} \quad (49)$$

$$RI = w_{RE} RE(t) + w_{RR} RR(t) + w_{DE} DE(t) + w_{RC} RC(t) + w_{RM} RM(t) + w_{PM} PM(t) \quad (50)$$

where *RI* represents the reconfigurability assessment towards SMS. The re-configurability assessment summarised the facts quantitatively and/or qualitatively. They are grouped in absolute or relative measures. Therefore, the re-configurability assessment will be used to achieve this goal and to increase companies' understanding the concept of I4.0 and promote its practical application. The re-configurability assessment index is typically used to measure quantitatively values. The w_{RE},w_{RR},w_{DE},w_{RC},w_{RM} and w_{PM} are the relative weights of the requirements of I4.0, requirements of reconfiguration, designing hybrid manufacturing systems, challenges of reconfiguration, reconfiguration methodology and performance measurements, respectively.

4 An illustrative example

This illustrative example is used to demonstrate the proposed framework for assessing the reconfiguration towards I4.0. Data related to requirements of I4.0 (RE), requirements of reconfiguration (RR), designing hybrid manufacturing systems (DE), challenges of reconfiguration (RC), reconfiguration methodology (RM), and performance measurements (PM) are shown in the following Table (3).

The data included in Figure 9 is used to estimate the relative weights between streams towards SMS. It can be seen from the AHP matrix in Figure 9 that the relative weights between streams were estimated and proposed by stakeholders. It was noticed that requirements of I4.0 (RE) were estimated to be three times more important than the requirements of reconfiguration (RR) and equivalent important to designing hybrid manufacturing systems (DE) and twice more important than challenges of reconfiguration (RC) and reconfiguration methodology (RM) and three times more important than performance measurements (PM). The RR was estimated to be equivalent important to DE, RC, and RM, and twice more important than (PM). The DE was estimated to be half as crucial as RC, and equivalent to RM and twice more critical than PM. The RC was estimated to be equivalent important to RM, and twice more critical than PM. The RM was estimated to be equivalent important to PM. The random index (RI) is selected from Figure 9 for n = 6 as 1.240. Then, the consistency index, CI/RI equals 0.0355. Because CI/RI is sufficiently small, the decision maker's comparisons are probably sufficiently consistent with providing useful estimates of the weights.

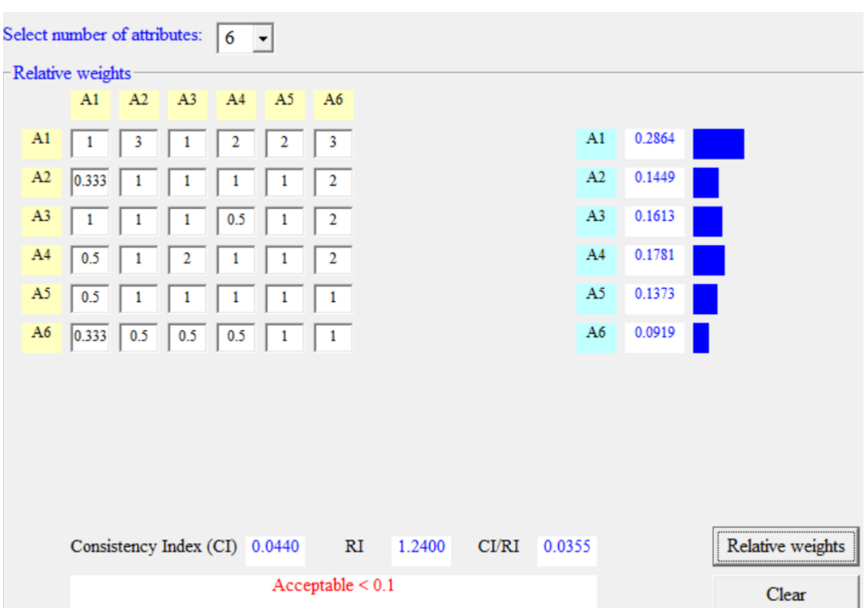
In this case, the result is accepted because the inconsistency ratio equals 0.0355, and it is less than 0.10. As a result, the relative weights are estimated for stream toward SMS as (0.2864, 0.1449, 0.1613, 0.1781, 0.1373, and 0.0919) for RE, RR, DE, RC, RM, and PM (see Figure 9). These relative weights can be changed based on the perspective of the stakeholders of the XYZ Company. This means that these values can be changed from one time to another time based on also new circumstances and requirements.

Therefore, the reconfigurability index toward SMS based on Equation (50) is rewritten as the following Equation (51) relied on the assessment of the proposed relative weights from the stakeholders and indexes from Table 3 with using Equations (6–47). The index of each stream and the reconfigurability index are shown in Table 4 and Equation (51). It seems from the results obtained of the reconfigurability index (RI), which equals 42.40%, that the infrastructure of the production systems achieved only 42.40% of the total requirements toward SMS (I4.0). This means that it needs 57.60% more than the existing one(s) to achieve I4.0. It can be noticed from Table 4 that the requirements of each stream are different from others, but most of them still need more required infrastructure.

$$\begin{aligned} RI(t) = (0.287)RE(t) + (0.145)RR(t) + (0.161)DE(t) + (0.178)RC(t) \\ +(0.138)RM(t) + (0.092)PM(t) \\ \therefore RI(t) = 0.4239 = 42.4\% \end{aligned} \tag{51}$$

The stream of requirements of I4.0 (RE) represents the lowest value of setup by 29% follows by requirements of reconfiguration (RR) by 33.80% and by 40%, 41.5%, 55% and 75% for designing of hybrid manufacturing systems (DE), challenges of reconfiguration (RC), performance measurements (PM), and reconfiguration methodology (RM), respectively.

Figure 9 Relative weights between the streams towards SMSs (see online version for colours)



The degree of importance of each stream in value and percentage (%) regarding the reconfigurability index is (0.424, 42.40%), and (1,000, 100%), respectively. It can be observed from Table 5 that RM and RE represent the highest percentage following by RC, DE, PM, and RR (Table 5).

Table 5 Analysis of each stream

	RI(t) value	*RI(t)-value*	*RI(t)%*	*RI(t)-%*
RE	8.30	42.40	19.57	100
RR	4.90		11.55	
DE	6.45		15.21	
RC	7.40		17.45	
RM	10.3		24.30	
PM	5.05		11.90	

It was noticed from the results obtained from Table 5 that the reconfiguration methodology (RM) needs more attention to be investigated and studied. Although the requirements of I4.0 (RE) represents the second rank of importance by 19.57% and these requirements are considered constant and well known for all industrialists and practitioners, they need more deeply analysis especially the advanced manufacturing application 'technologies' and modularity. Almost the challenges of reconfiguration (RC) has approximately the same importance of RE (17.45%). These challenges will be remain as they are because of the manufacturing complexity, reconfigurable machines, competitive manufacturing strategies and CPSs (automation level, sensors and actuators).

Designing a hybrid manufacturing system (DE) is still undergoing from the manufacturing systems designers and it is still more considerations from academicians and industrialists. With respect to the requirements of reconfiguration (RR) and performance measurements (PM), they have almost the same percentage of importance (11.55% and 11.90%), respectively). Regarding RR, the requirements are general for the first three requirements (B1–B3) but it has more attention for I4.0 (B4 and B5). The same comment is added to PM, six of the PMs (F1–F6) are used for traditional manufacturing systems and additional two more PMs (F7 and F8) are recommended for performance evaluation for smart manufacturing.

5 Conclusions, contribution and recommendation for future work

A framework towards analysis and design SMS s was presented through six main streams starting from the requirements of I4.0 and requirements of reconfiguration issues following by designing manufacturing systems, challenges of reconfiguration, and reconfiguration methodology and its associated performance measurements. It was noticed that modularity is one of the six design principles of I4.0 matched with the advanced manufacturing solutions as one of the nine pillars of enabling technologies. It was noticed that modularity, flexibility, agility, and advanced manufacturing solutions have focused on the requirements of reconfiguration. There is also a relationship between designing hybrid manufacturing systems and challenges of reconfiguration. Not all enablers of reconfiguration methodology matching with performance measurements accept the type of manufacturing system. It was seemed that the physical systems with different aspects of layouts need to be automated, and the level of difficulty in implementing I4.0 was low in terms of automation, sensors, and actuators.

5.1 Theoretical significance

A novel approach for identifying the re-configurability index was suggested, analysed and presented through an illustrative numerical example through six main streams of reconfiguration issues. These streams which were represented by requirements of I4.0; requirements of reconfiguration issues; designing manufacturing systems; challenges of reconfiguration; reconfiguration methodology and performance measurements deserve a big attention from academicians and industrialists. The target values of each element in re-configurability stream (maximum, minimum) and the actual value have been used for normalising re-configurability index. This theoretical study is oriented for investigation in re-configurability index in the whole manufacturing systems.

5.2 Managerial implications

Manufacturing system design and infrastructure maybe a hurdle for the smooth transformation into I4.0 because most of industrial organisations especially traditional ones may not be ready to transfer for I4.0 not only in developed countries but also in emerging and developing countries. For this reason, analysis the re-configurability index for the existing manufacturing systems towards implementing I4.0 is necessary to be studied. Studying and analysing the requirements of I4.0; requirements of reconfiguration issues; designing manufacturing systems; challenges of reconfiguration; and reconfiguration methodology and its associated performance measurements is still highly appreciated. This study shows that it is very urgent to identify the re-configurability index in each stream taken into consideration the major common element of it with identifying the target values.

5.3 Contributions and recommendations for future research directions

This paper's main contribution is to present a framework for all streams and propose a re-configurability index toward designing manufacturing systems to achieve I4.0. This framework is used to illustrate the steps and procedures to estimate the re-configurability index for each stream by identifying the significant enablers for each one. The authors intend to extend future research to include the real-life case studies.

Acknowledgements

The authors would like to thank the anonymous reviewers for valuable and useful feedback comments that contributed to an improvement of this paper.

References

Andersena, A-L., ElMaraghy, H., ElMaraghy, W., Brunoea, T.D., and Nielsena, K. (2017) 'A participatory systems design methodology for changeable manufacturing systems', *International Journal of Production Research*, Vol. 56, No. 8, pp.2769–2787.

Azevedo, M.M., Crispim, J.A. and De Sousa, J.P. (2017) 'A dynamic multi-objective approach for the reconfigurable multi-facility layout problem', *Journal of Manufacturing Systems*, Vol. 42, pp.140–152.

Bashir, H., Garbie, I., Hejaaji, A. (2020) 'Reconfiguration of hospital outpatient pharmacies by adopting the concept of group technology for arrangement of drugs on shelves', *International Journal of Industrial and Systems Engineering*, Vol. 36, No. 3, pp.430–450.

Bauer, H., Brandl, F., Lock, C. and Reinkart, G. (2018) 'Integration of Industrie 4.0 in lean manufacturing learning factories', *Procedia Manufacturing*, Vol. 23, pp.147–152.

Bortolini, M., Ferrari, E., Gamberi, M., Pilati, F. and Faccio, M. (2017) 'Assembly system design in the Industry 4.0 era: a general framework', *IFAC Papers Online*, Vol. 50, No.1, pp.5700–5705.

Bortolini, M., Gabriele, F.G. and Mora, C. (2018) 'Reconfigurable manufacturing systems: literature review and research trend', *Journal of Manufacturing Systems*, Vol. 49, pp.93–106.

Cohen, Y., Faccio, M., Galizia, F.G., Mora, C. and Pilati, F. (2017) 'Assembly system configuration through Industry 4.0 principles: the expected change in the actual paradigms', *IFAC Papers online*, Vol. 50, No. 1, pp.14958–14963.

Deif, A.M. and ElMaraghy, H.A. (2017) 'Variety and volume dynamic management for value creation in changeable manufacturing systems', *International Journal of Production Research*, Vol. 55, No. 5, pp.1516–1529.

Dombrowski, U., Richter, T. and Krenkel, P. (2017) 'Interdenencies of Industrie 4.0 and lean production systems – a use cases analysis', *Procedia Manufacturing*, Vol. 11, pp.1061–1068.

ElMaraghy, H. and ElMaraghy, W. (2016) 'Smart adaptable assembly systems', *Procedia CIRP*, Vol. 44, pp.4–13.

Garbie, I. and Al-Shaqsi, R. (2019) 'Building sustainable models and assessments into petroleum companies: theory and application', *International Journal of Industrial and Systems Engineering*, Vol. 33, No. 4, pp.473–512.

Garbie, I. and Garbie, A. (2020a) 'Outlook of requirements of manufacturing systems for 4.0', *The 3rd International Conference of Advances in Science and Engineering Technology (Multi-Conferences) ASET 2020*, Dubai, UAE, 4–6 February, 5pp.

Garbie, I. and Garbie, A. (2020b) 'A new analysis and investigation of sustainable manufacturing through a perspective approach', *The 3rd International Conference of Advances in Science and Engineering Technology (Multi-Conferences) ASET 2020*, Dubai, UAE, 4–6 February, 5pp.

Garbie, I. and Garbie, A. (2020c) 'Sustainability and manufacturing: a conceptual approach', *Proceedings of the Industrial and Systems Engineering Research Conference (IISE Annual Conference and Expo 2020)*, New Orleans, LA, USA, 1–3 November, 6pp.

Garbie, I.H. (2014a) 'A methodology for the reconfiguration process in manufacturing systems', *Journal of Manufacturing Technology Management*, Vol. 25, No. 6, pp. 891-915.

Garbie, I.H. (2016) Sustainability In Manufacturing Enterprises- Concepts, Analyses, And Assessments For Industry 4.0, Springer International Publishing Switzerland.

Garbie, I.H. (2017) 'Identifying challenges facing manufacturing enterprises towards implementing sustainability in newly industrialized Countries', *Journal of Manufacturing Technology Management (JMTM)*, Vol. 28, No. 7, pp.928–960.

Garbie, I.H. (2014b) 'Performance analysis and measurement of reconfigurable manufacturing systems', *Journal of Manufacturing Technology Management*, Vol. 25, No. 7, pp.934–957.

Haleem, A., Javaid, M., Khan, S. and Khan, M.I. (2020) 'Retrospective investigation of flexibility and their factors in additive manufacturing systems', *International Journal of Industrial and Systems Engineering*, Vol. 36, No. 3, pp.400–429.

Ingole, S. and Singh, D. (2021) 'Fixed and flexible shape facility layout problems using biogeography-based optimization algorithm', *International Journal of Industrial and Systems Engineering*, Vol. 37, No. 1, pp.84–118.

Kolberg, D. and Zuhlke, D. (2015) 'Lean automation enabled by industry 4.0 technologies', *IFAC-Papers Online*, Vol. 48, No. 3, pp.1870–1875.

Kusiak, A. (2018) 'Smart manufacturing', *International Journal of Production Research*, Vol. 56, Nos. 1–2, pp.508–517.

Lu, Y. (2017) 'Industry 4.0: a survey on technologies applications and open research issues', *Journal of Industrial Information Integration*, Vol. 6, pp.1–10.

Mohtashami, A., Alinezhad, A. and Niknamfar, A.H. (2020) 'A fuzzy multi-objective model for a cellular manufacturing system with layout designing in a dynamic condition', *International Journal of Industrial and Systems Engineering*, Vol. 34, No. 4, pp.514–543.

Moty, B., Baronio, G., Uberti, S., Speranza, D. and Filippi, S. (2017) 'How will change the future engineers 'skills in the Industry 4.0 framework? A questionnaire survey', *Procedia Manufacturing*, Vol. 11, pp.1501–1509.

Neugebauer, R., Hippmann, S., Leis, M. and Landherr, M. (2016) 'Industrie 4.0 - from perspevtive of applied research', The *49th CIRP Conference on Manufacturing systems, (CIRP-CMS)*, *Procedia CIRP*, Vol. 57, pp.2–7.

Prasad, D. and Jayswal, S.C. (2018) 'Reconfigurability consideration and scheduling of products in a manufacturing industry', *International Journal of Production Research*, Vol. 56, No. 19, pp.6430–6449.

Reischauer, G. (2018) 'Industry 4.0 as policy-driven discourse to institutionalize innovation systems in manufacturing', *Technological Forecasting and Social Change*, Vol. 132, pp.26–33.

Samant, S. and Prakash, R. (2021) 'Achieving lean through value stream mapping with constraint programming and simulation technique for complex production systems', *International Journal of Industrial and Systems Engineering*, Vol. 37, No. 1, pp.119–148.

Santos, M.Y., Oliveita, J., Andrade, C., Lima, F.V., Costa, E., Costa, C., Martinho, B. and Galvao, J. (2017) 'A big data system supporting Bosch Braga Industry 4.0 strategy', *International Journal of Information Management*, Vol. 37, pp.750–760.

Scheuermann, C., Verclas, S. and Bruegge, B. (2015) 'Agile factory-an example of an Industry 4.0 manufacturing process', *2015 IEEE 3rd International Conference on Cyber-Physical Systems, Networks, and Applications*, 5pp.

Suer, G. (2014) 'Cellular manufacturing systems', *A Keynote Speaker, International Conference on Computers and Industrial Engineering joint with International Symposium on Intelligent Manufacturing and Service Systems (CIE 44 and IMSS'14)*, Istanbul, Turkey, 14–16 October.

Tiwari, R.K. and Tiwari, J.K. (2019) 'Identification of key lean practices within Indian automotive SMEs environment', *International Journal of Industrial and Systems Engineering*, Vol. 33, No. 1, pp.17–37.

Tiwari, R.K. and Tiwari, J.K. (2020) 'Prioritisation of attributes of green leanness and agility to achieve sustainable strategic advantages in Indian automotive SMEs environment', *International Journal of Industrial and Systems Engineering*, Vol. 36, No. 3, pp.316–338.

Tupa, J., Simota, J. and Steiner, F. (2017) 'Aspects of risk management implementation for industry 4.0', *Procedia Manufacturing*, Vol. 11, pp.1223–1230.

Varela, M.L.R. Manupati, V.K., Panigrahi, S., Costa, E. and Putnik, G.D. (2020) 'Using social network analysis for industrial plant layout analysis in the context of Industry 4.0', *International Journal of Industrial and Systems Engineering*, Vol. 34, No. 1, pp.1–19.

Wagner, T., Herrmann, C. and Thriede, S. (2017) 'Industry 4.0 impacts lean production systems', The *50th CIRP Conference in Manufacturing Systems, Procedia CIRP*, Vol. 63, pp.125–131.

Wang, S., Wan, J., Li, D. and Zhang, C. (2016) 'Implementing smart factory of Industrie 4.0: an outlook', *International Journal of Distributed Sensor Networks*, Vol. 2016, 10 pages, http://dx.doi.org/10.1155/2016/3159805.

Zhang, X., Ming, X., Liu, Z., Yin, D. and Chen, Z. (2019) 'A reference system of smart manufacturing talent education (smte) in China', *The International Journal of Advanced Manufacturing Technology*, Vol. 100, pp.2701–2714.